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Tim Miller, "Mixed-Mode Fracture in a Rubbery Particulate Composite"

(Statement A)

Extended Abstract

MIXED-MODE FRACTURE IN A RUBBERY PARTICULATE COMPOSITE

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INTRODUCTION

Often cracks in rubbery particulate composites are found in the propellant grain of rocket motors and experience mixed-mode loading. These composites are made from a rubbery matrix with a high volume of rigid particles (70-80%). The cracks threaten structural integrity and can grow to catastrophic failure. Refinements in our predictive abilities yield cost savings by improving service life predictions. This work uses an approximate analysis to examine the crack behavior. This approach is practical and useful because it can be put to widespread use in industry.

EXPERIMENTAL PROCEDURE

We used center cracked specimens, 101.6 mm x 101.6 mm x 5.08 mm, with 25.4 mm center cracks oriented at an angle β with the horizontal. Different crack orientations provided specimens with different mode mixities. For these specimens, the phase angle of the complex stress intensity factor was approximately equal to the crack orientation angle β. We tested two specimens at each of the crack orientations (0°, 15°, 30°, 45°, and 60°), applying uniform vertical displacements to the horizontal specimen edges at a constant 5.08 mm/min rate. We measured the initiation loads and growth rates from videotape; we measured the initial growth directions from the fractured specimens after testing. The initiation loads were used with finite elements to determine the components (K_{IC} and K_{IIC}) of the initiation toughness.

RESULTS

We obtained all the results shown by applying linear elastic fracture mechanics concepts to a rubbery composite that has viscoelastic properties capable of high elongations. This approach is justified because the fracture initiation and growth occur on the linear part of the stress-strain curve and because moiré experiments show linear elastic behavior near cracks in these composite specimens. However, because of the time dependent constitutive behavior, the results must be applied to structures with similar nominal strain rates. This use of linear elastic fracture mechanics is practical because by greatly simplifying analyses that would otherwise be cumbersome and unfeasible it allows for widespread use.

The fracture toughness locus for the mixed-mode tests, shown in Figure 1, has an elliptical curve fit of the form:

$$\left(\frac{K_I}{K_{IC}}\right)^2 + \left(\frac{K_{II}}{K_{IIC}}\right)^2 = 1 \tag{1}$$

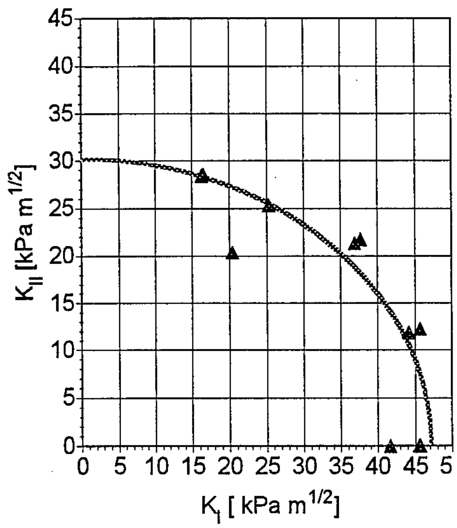

Figure 1 Elliptical failure locus

We treated the parameters K_{IC} and K_{IIC} as unknowns and determined them using least-squares. Equation (1) is regarded as linear in the unknowns $(1/K_{IC})^2$ and $(1/K_{IIC})^2$, and the least-squares method is applied using matrix algebra [1]. Researchers have used an elliptical curve fit previously for isotropic materials. Note that the pure mode II fracture toughness is smaller than its mode I counterpart. Previous explanations that examined the fracture toughness locus in relation to micromechanisms were based on observations from metals, and do not seem to apply to rubbery composites. Determining the connection to microstructure is left for future work, but two possibly relevant phenomena are suggested: the presence of rubbery ligaments behind the crack tip and the growth of voids from particles near the crack tip.

We used the experimentally determined loads with finite elements to determine the J integral and then to derive K_{IC} and K_{IIC}. Using the crack face displacement data, it was determined that for these specimens the complex stress intensity factor phase angles were approximately equal to the crack orientation angles. Then, using $J_c = K_c^2/E$, where K_c is the magnitude of the complex fracture toughness, and $\Psi = \beta$, where Ψ is the phase angle, allows K_{IC} and K_{IIC} to be calculated.

The initial growth directions, or kink angles, were determined by experiment and are shown in Figure 2. This figure also shows predicted kink angles from several theories, all of which gave similar results [2,3]. The large deformations during actual loading made it difficult to unambiguously determine the kink angles, so we measured them after testing by projecting the fractured surfaces onto a large screen.

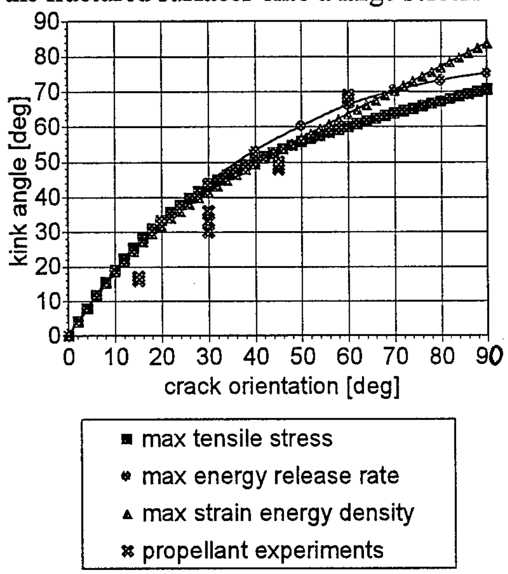

Figure 2 Kink angles vs. crack orientation angle

We measured the growth rates from videotape using the approach of Figure 3. During most of the growth, the angled crack of Figure 3a experiences mode I growth that can be characterized by the effective crack length and related mode I stress intensity factor of Figure 3b. The crack growth rate and K_I can be related through a power law relation such as:

$$\frac{da_{eff}}{dt} = CK_I^m \qquad (2)$$

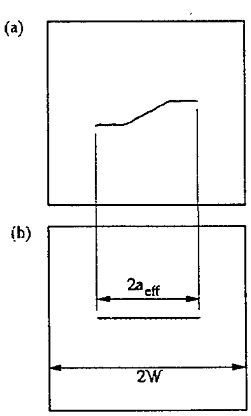

Figure 3 Modeling mixed mode crack growth

This gives nearly identical results for all the tested mode mixities. Because of this, the growth of a mixed-mode crack with a geometry shown in Figure 4a can be modeled using the simplified geometry of Figure 4b. Figure 5 shows the aggregate data and resulting curve fit; the parameters in eqn (2) are $C = 1.79 \times 10^{-6}$ and $m = 2.73$. Results for a mode I specimen gave the nearly identical results of $C = 1.85 \times 10^{-6}$ and $m = 2.74$.

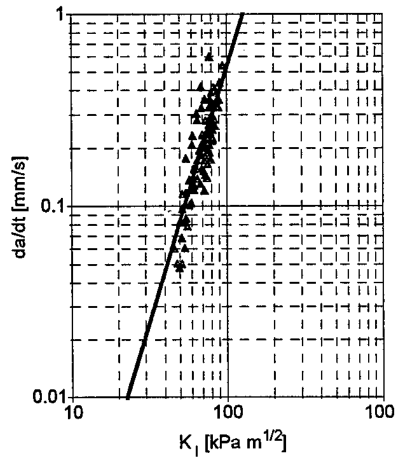

Figure 5 Effective crack growth rate vs. K_I

CONCLUSIONS

Although rubbery particulate composites have viscoelastic properties, high elongations, and complicated failure mechanisms, they can be studied, for a given nominal strain rate, using the principles of linear elastic fracture mechanics. When analyzed like this, the fracture locus is elliptical. The initial crack growth angles match the strain energy density predictions best, although for all but the highest mode mixities, other theories gave nearly identical results. The crack growth rates can be predicted using an approximate mode I approach. The result is a simple approach that circumvents more detailed and difficult analyses. Future work could include experimental methods to study the causes of fracture in these composites, especially the micromechanisms near the crack tip at various mode mixities.

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